Collimated Outflow Formation via Binary Stars. 3-D Simulations of AGB Wind and Disk Wind Interactions

F. García-Arredondo

and

Adam Frank

Department of Physics and Astronomy, University of Rochester

Rochester, NY 14627-0171

fgarcia@pas.rochester.edu, afrank@pas.rochester.edu

ABSTRACT

We present three-dimensional hydrodynamic simulations of the interaction of a slow wind from an asymptotic giant branch(AGB) star and a jet blown by an orbiting companion. The jet or "Collimated Fast Wind" is assumed to originate from an accretion disk which forms via Bondi accretion of the AGB wind or Roche lobe overflow. We present two distinct regimes in the wind-jet interaction determined by the ratio of the AGB wind to jet momentum flux. Our results show that when the wind momentum flux overwhelms the flux in the jet a more dis-ordered outflow outflow results with the jet assuming a corkscrew pattern and multiple shock structures driven into the AGB wind. In the opposite regime the jet dominates and will drive a highly collimated narrow waisted outflow. We compare our results with scenarios described Soker & Rappaport (2000) and extrapolate the structures observed in PNe and Symbiotic stars.

Subject headings: binaries: close—planetary nebulae: general—stars: AGB and post-AGB

1. Introduction

The role of binary stars in the shaping of planetary and proto-planetary nebulae (PN, pPNe) has been a topic of debate for many years (Bujarrabal et al. 2000). PNe occur in a wide variety of shapes ranging from spherical, elliptical, narrow-waisted bipolar and bi-lobed (an elliptical core with projecting bipolar lobes). Some PNe also show narrow jet-like features. pPNe show striking bipolar or jet like morphologies and recently this brief evolutionary phase has been identified as the period during which much of the shaping occurs. Much of the theorizing on how pPNe and PNe obtain their shapes has included, either implicitly or explicitly, the presence of a binary companion (see Balick & Frank (2002) for a review of PNe shapes and shaping mechanisms).

Hydrodynamic Generalized Interacting Stellar Wind (GISW) models, in which successive wind phases from a single evolving AGB star sculpt the nebula, were believed to hold considerable promise for some time (Balick 1987; Icke, Preston, & Balick 1989). In these scenarios fast winds from the PNe central star expand into an aspherical slow wind expelled by the AGB progenitor. These models did not explicitly require the presence of a companion but it was often assumed that the shaping of the slow wind occurred via tidal or common envelope interactions (Livio 1993).

While hydrodynamic models were successful at recovering many elliptical and bi-lobed nebula, simulations demonstrated that the more extreme "wasp-waisted" bipolars could not be easily recovered (Icke, Balick, & Frank 1992; Mellema 1995; Dwarkadas, Chevalier, & Blondin 1996). In addition many PNe and pPNe (particularly, but not limited to, those with jets) show point-symmetric morphologies in which nebular features are reflected around the central star (Sahai & Trauger 1998). Such features are difficult to explain with purely hydrodynamic models. More recently a new problem has emerged as it has been recognized that radiation wind driving alone can not be responsible for the momentum and energy budgets associated with pPNe (Bujarrabal et al. 2001).

The failure of pure hydrodynamic models have led researchers to consider MHD scenarios for PNe formation. Of particular interest are models in which the magneto-centrifugal forces from an accretion disk (Konigl & Pudritz 2000) both launch the wind and collimate it into a jet. Blackman, Frank, & Welch (2001) and Frank & Blackman (2003) have shown that MHD disk wind models can be quite effective at driving outflows with the total momentum and energy observed in pPN and PN. We note that weak magnetic field models are, by their nature, unable to produce observed pPN momenta and we do not consider them here (García-Segura et al. 1999).

Of course, any model which requires an accretion disk will, in the context of PNe, require a binary system. Observationally there exist strong links which argue that disks winds and jets from binary companions play a significant role in pPNe and PNe shaping. Close binary PNe central stars are know to exist (Bond 2000) indicating that interactions between stellar mass loss processes are likely to occur at some point. More telling are the example of the symbiotic stars. These are binary stars in which a compact companion is known to orbit an AGB star. There a numerous examples of highly collimated outflows from these systems that appear quite similar to PNe (Corradi et al. 2000).

Morris (1987) and Soker & Livio (1994) where the first to identify accretion disks from binaries as the source of highly collimated PNe. A number of studies have explored the formation and properties of the these disks (Mastrodemos & Morris 1998, 1999) and the nature of the binary systems which would form them. More recently Soker & Rappaport (2000) have considered the existence of Collimated Fast Winds (CFWs) from an orbiting companion's disk and sketched out the flow pattern which would occur as the CFW interacts with the AGB wind. Livio & Soker (2001) applied such a model to M2-9 demonstrating that the resulting flow pattern could, in principle, be embraced by the interaction of a CFW and AGB wind.

In this paper we use 3-D adaptive mesh hydrodynamical simulations to explore the hydrodynamics of AGB wind/CFW interactions. In particular we focus on explicit realizations of the flow patterns near the two stars in an attempt to understand the limits of this class of models. Carrying forward simulations such as these pose a number of numerical challenges and here we attempt to explore only the fundamentals of the hydrodynamics. We note that our models represent the first numerical exploration of this important class of model and should serve to help articulate key issues related to their application and further study.

The structure of our paper is as follows. In section II we describe the numerical model, assumptions and simplifications used in our calculations. In section III we describe our results and in section IV we present a discussion of their implications as well as our conclusions.

2. Numerical Simulations

2.1. Numerical methods and equations

We work in the regime of ideal gas dynamics in the presence of gravitational sources. Thus we solve the Euler equations, which, in conservative form are

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \quad , \tag{1}$$

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot (\rho \mathbf{v}\mathbf{v} + p\mathbf{I}) = -\rho \nabla \Phi \quad , \tag{2}$$

$$\frac{\partial E}{\partial t} + \nabla \cdot (\mathbf{v}[E + p]) = -\rho \mathbf{v} \cdot \nabla \Phi \quad , \tag{3}$$

where ρ, $\mathbf{v}$ and p are the density, velocity and pressure at a point of the fluid, respectively, $\mathbf{vv}$ is the tensor product and $\mathbf{I}$ is the unit tensor. E is the total energy per unit of volume, given by

$$E = \frac{p}{\gamma - 1} + \frac{1}{2}\rho |\mathbf{v}|^2 \quad . \tag{4}$$

In addition, we had included an advection equation for a passive scalar, which will be used for tracing the different flows. Here, gravity is due solely to the stellar sources and self gravity is not included. The gravitational source term is given by

$$\nabla \Phi = G \left(\frac{M_{\rm AGB}\mathbf{r}}{|\mathbf{r}|^3} + \frac{M_{\rm c}(\mathbf{r} - \mathbf{r}_{\rm c})}{|\mathbf{r} - \mathbf{r}_{\rm c}|^3} \right) \quad , \tag{5}$$

where $M_{\rm AGB}$ and $M_{\rm c}$ are the masses of the AGB and its companion, respectively, and $\mathbf{r}_{\rm c}$ is the position of the companion. The gravitational source term is handled in an operators split fashion via a first order integration carried out between hydrodynamic time-steps.

The numerical simulations are carried out using a version of the yguazú-a adaptive code, described by Raga, Navarro-González, & Villagrán-Muñiz (2000). This code is well tested and has been used for a variety of supersonic flow problems. The hydrodynamic equations are numerically integrated on an adaptive mesh refined using a second order flux vector splitting scheme with a Van Leer (1982) algorithm. We used four levels with $640 \times 320 \times 320$ cells on the maximum level. The boundary conditions are transmission for both x and y boundaries as well as the maximum z boundary. A reflecting boundary condition is used on the lower z axis, due to the symmetry of the problem.

We have carried out our simulations assuming an approximate isothermal flow. Thus we choose $\gamma = 1.01$. Since our simulations are carried out close to the stars the densities in the flow are quite high ($\rho \approx 10^{-18}$ g cm^{-3}) and the cooling times will be shorter than what are usually considered in nebular problems. In spite of the high densities the temperature structure behind high velocity shocks, $V_{\rm s} \approx 1000$ km s^{-1}, are likely to be complex and post-shock gas may not immediately cool. In such cases a time-dependent treatment of the cooling should be used. In this paper we only explore cases with lower velocities where the cooling timescales will be relatively short compared with dynamical times and the isothermal assumption is acceptable.

2.2. Initial Conditions

Our simulations were designed to explore the interaction of a collimated wind from an orbiting companion interacting with the spherical outflow from the AGB primary. We do not attempt to explore the formation of accretion disks and simply apply an inflow condition at the location at the instantaneous position of the companion. As we discuss below however, we have chosen binary parameters which are expected to lead to the formation of an accretion disk. We note that these simulations are computationally intensive. We made a number of assumptions and simplifications which allowed a trade-off between remaining in the correct parameter regime and resolution/computation resource issues.

For the AGB wind we assume typical values of parameters. We begin with a 1.4 $M_\odot$, star driving a spherically symmetric, mass-loss of rate $\dot{M}_{\rm AGB} = 10^{-6}$ $M_\odot$ yr^{-1}. We take the radius of AGB to be a "wind release" radius of $r_{\rm AGB} = 4$ AU. This is the point at which we inject the wind into the grid with $v_{\rm AGB}(r_{\rm AGB}) > v_{\rm esc}(r_{\rm AGB})$. Given the computational requirements needed for the hydrodynamics alone we do include radiation driving on dust in the wind which would produce a gradual acceleration until an terminal velocity is reached at $r >> r_{\rm AGB}$. Instead the wind follows a type III solution to the classic parker wind equation (Raichoudhuri 1998)

$$(v^2 - c^2)\frac{dv}{dr} = \left(\frac{2c^2}{r} - \frac{GM}{r^2}\right) v \quad , \tag{6}$$

where c is the sound velocity. Given our boundary conditions at $r_{\rm AGB}$ our wind first decelerates due to gravity and then reaccelerates on a trajectory similar to the radiation-driven wind. Thus

the radial wind structure of the wind close to the star departs from dust-driven wind models. Note that the wind is always supersonic. We have carried out simulations in which we move the inflow boundary further outward such that the wind velocity remains relatively constant and have found no change in the global flow patterns.

For our companion we chose a .6 $M_\odot$ star with orbital separation $a = 10$ AU. We assumed a spherical orbit with resulting orbital period of $T_o \approx 22.4$ years. We note that our simulations are carried out with the AGB primary fixed to the origin of the coordinate system. We do not attempt to treat the reflex motions of the companion. This greatly reduces the complexity of the boundary conditions on both AGB star and the jet. Comparison of the various velocities in the problem demonstrates that such an assumption should not change the global flow patterns we attempt to explore. If $v_1 = \sqrt{G}M_c(M_{AGB} + M_c)^{-1/2}a^{-1/2}$ is the velocity of the primary about the center of mass we require a hierarchy of velocities $v_j >> v_{AGB} > v_1$. For our parameters we find that at $v_1/v_{AGB} = 0.16$. Therefore, we expect that the reflex motions should not have a dramatic effect our results.

Based on the description of Soker & Rappaport (2000) we have chosen to explore two cases for the properties of the jet. For "Weak Jet" case, the momentum flux from the AGB star is larger than the that from the jet. We define a parameter χ

$$\chi = \frac{\dot{M}_{AGB} v_{AGB}}{\dot{M}_j v_j} \tag{7}$$

where the subscript "j" refers to properties of the jet. The Weak Jet models have $\chi > 1$ whereas the "Strong Jet" case has $\chi < 1$. In the two Weak Jet simulation we present we used $v_j = 200$ km s^{-1}, $\dot{M}_j = 10^{-7}$ $M_\odot$ yr^{-1}, and $\dot{M}_j = 2.5 \times 10^{-8}$ $M_\odot$ yr^{-1}, which yield $\chi = 1.25$, and $\chi = 5$. In the Strong Jet case the $v_j = 400$ km s^{-1}, and $\dot{M}_j = 10^{-7}$ $M_\odot$ yr^{-1} yielding $\chi = 0.625$. We note that values for the parameters taken for the jet are appropriate to an outflow driven by a main-sequence companion where $v_j \approx v_{esc}$. In our simulations the jet is not fully collimated. At the instantaneous position of the companion we inject a flow with the angle of collimation 10 degrees. Note also that our strong jet parameters imply that the companion accretes a large fraction of the AGB wind. This may not be realistic but was chosen to allow us to use a lower jet speed and maintain the isothermal assumption for the computations.

To have a produce a collimated jet it is necessary for an accretion disk to form around the secondary star. As discussed in Soker & Rappaport (2000) and elsewhere, a disk can be formed when the specific angular momentum of accreted material j_a is larger than the specific angular momentum of the accretor j_2 (the companion in a Keplerian orbit) *i.e.* $j_a/j_2 > 1$. From Soker & Rappaport (2000)

$$\frac{j_a}{j_2} = 15 \left(\frac{\eta}{0.2}\right) \left(\frac{M_{AGB} + M_c}{1.2 M_\odot}\right)^{1/2}$$

$$\times \left(\frac{M_2}{0.6 M_\odot}\right)^{3/2} \left(\frac{R_2}{0.01 R_\odot}\right)^{-1/2}$$
$$\times \left(\frac{a}{10\ \mathrm{AU}}\right)^{-3/2} \left(\frac{v_\mathrm{r}}{15\ \mathrm{km\ s^{-1}}}\right)^{-4} \quad (8)$$

where η is the ratio of the specific angular momentum of accreted material to that in material that enters the Bondi-Hoyle, cylinder (Livio et al. 1986; Soker & Rappaport 2000). $v_\mathrm{r}^2 = (v_\mathrm{AGB}^2 + v_2^2)$ is the relative velocity of the wind and companion. We take $\eta = 0.2$ which applies to a case where the accretion lies between an fully isothermal and adiabatic flows and $R_2 = .6\ R_\odot$. At $r = a$ we find a wind speed of $v_\mathrm{r} \approx 15$ km s^{-1} Thus we find $j_\mathrm{a}/j_2 \sim 2.5$ implying that a disk would form via accretion of the AGB wind. Detailed SPH simulations carried out by Mastrodemos & Morris (1998) using similar parameters as ours tracked the accretion flow and demonstrated that the formation of accretion disks was a robust result. An upper limit to the size of the disk can be calculated using the Bondi-Hoyle radius $R_a = 2GM_\mathrm{c}/v_\mathrm{r}^2 = 7 \times 10^{13}$ cm. A more exact relation for the disk radius is given in Livio & Soker (2001), from which we find $R_\mathrm{d} \approx 1.278 \times 10^{12}$ cm. This size of the disk is less than 1 pixel in our simulation ($\Delta x \approx .5$ AU at the highest resolution).

3. Results

In this section explore the flow pattern obtained in the Weak and Strong Jet cases and attempt to link these with previous theoretical and observational works.

3.1. Strong Jet

We begin with consideration of the strong jet case whose flow pattern is simpler to visualize and understand. In Figure 1 we present density grey scale maps of the Strong Jet simulation in the: (a) xz-plane: (b) yz-plane: (c) xy plane. The first two cross- sections run through the central axis of the computational space and the third is taken at the base of the flow and includes the AGB and companion/jet inflow boundaries. Figure 1 shows this simulation after 224 years, or 10 orbital periods.

With a momentum flux ratio of $\chi = 0.625$ one would expect that the jet material would be able to propagate through the AGB wind relatively unimpeded. If shocks do occur they will be found along the sides of the expanding jet column where the jet has pushed AGB material away, entraining and accelerating it. Most importantly we would do not expect the jet to be strongly deflected. The principle modification to jets motion could arise from the shift in its launch point due to the orbital motion of the companion. This will only occur when the orbital period T_o is comparable to the jet crossing time though the computational domain $T_\mathrm{cross} = H/v_\mathrm{j}$ where H is the height of the computational space. When $T_\mathrm{cross}/T_\mathrm{o} \geq 1$ then a corkscrew morphological pattern may be expected for the jet's 3-D structure. The spherical AGB wind, on the other hand, will be

strongly modified by the passage of jet material. AGB material whose trajectories cross the jet will have to be shocked and diverted. Since we do not expect strong shocks in the jet beam for our Strong Jet case, the velocity $v_{\rm j} = 400$ km s^{-1} is expected all the way up the jet. Thus $T_{\rm cross}/T_{\rm o} = .1$ and we will not expect much "twisting" in the jet morphology.

These expectations are born out by the simulations. Consider the xz and yz cross section in Fig 1 (panel a and b). Panel a) shows a broad **V**-shaped outflow "lobe" driven by the jet as it pushes through the AGB wind. The outer boundaries of the **V** are shock waves propagating through the expanding AGB wind. This shock creates a dense shell of compressed AGB material (see left panel detail). Note that this structure is not symmetric. The concave shell appears as a darker "bar" on the right side on plot a) with a weaker feature on the left. Note that similar pattern appears in plot b) but here the jet only appears at a higher value of z and there are stronger asymmetries between the left and right part of the grid. The asymmetry is a result of the 3-D nature of flow. Shocks are driven through the AGB as the jet sweeps through its orbit. Thus a given point in the computational space experiences the passage of a succession of strong pressure wave at intervals of approximately $T_{\rm o}$. Note also the high density structure which can be traced back to the jet source with a second low density region external to it (the lower-left panel of Figure 1. This feature may be due to the movement of the jet inflow boundary condition as new cells become injection points while others return to being reflection boundaries.

Another, nested, **V**-shaped feature comprised of lighter greyscales is also apparent. This defines the limits of the cavity carved out by the jet. Consideration of the details of the flow patterns show that propagation of the jet through the AGB material results in considerable entrainment of AGB gas (the darker greyscales immediately surrounding the jet) and the final state is one in which the accelerated AGB material fills a large volume of the cone defined by the global flow. This entrainment appears to occur via the oblique shocks which define interface of the jet/AGB flow. As the jet material is slowed and redirected via these shocks AGB material is accelerated and mixed into the shell which defines the cavity. Note the periodic structures at the edges of the jet. We conjecture that these features represent Kelvin-Helmholtz modes which are only just resolved in these simulations. These modes will enhance AGB acceleration and mixing at the interface of jet/AGB cavity.

Examination of Figure 1 shows how the orbital motion of the jet drives a positional interchange between the current location of the companion and the location where the strongest jet-AGB wind interaction will occur. In the enlargement of the lower region of panel (a), the xy cross section, we see the jet lies to the right of the AGB star. The lower density (lighter greyscale) material can be seen flowing in the z-direction in panel (a). Jet material which has been ejected earlier (and is at higher z) will be further up the beam and deeper into the 3-D volume then the position of this xy cut. The dark greyscales which bound the jet are "sideways" shocks which result when ever a jet flow changes its directions. Such features have been seen and described in simulations of precessing jets (Raga, Cantó, & Biro 1993; Cliffe, Frank, & Jones 1996). The shift in position of the jet and shock features is also apparent in panel (b) which shows the yz plane. Here the

lower density features which appear above the AGB star is jet material. This structure occurs both because the opening angle of the jet and its orbital movement. In this simulation the jet is strong enough that its core remains undisturbed until it leaves the grid. We do some mild orbital effects in the jet morphology reflected in the apparent change in direction of jet beam in panel a) at the top of the grid where the lightest contours terminate. In the top of panel b) however the lightest contours representing undisturbed jet extend to the edge of the grid.

The global morphology of the jet-AGB wind interaction can be seen in Fig 2. This figure shows a 3-D volume rendering of the velocity along with an iso-surface represented as a wire-frame mesh. Here we can clearly see that the jet has only a small trace of a corkscrew pattern and that it is the expansion of the jet and the entrainment of AGB material which contribute most strongly to the velocity (and hence density) pattern. The entrainment of shocked AGB wind with shocked jet material is particularly apparent in this figure as the jet is surrounded by lower velocity gas. We see shocked/mixed AGB material at a wide range velocities with the highest speeds reached being $v \sim 250$ km s^{-1}. Note also the arc of material defined by the wireframe. This feature defines the wake of the jet and companion though the AGB gas via spiral shocks.

The behavior of the flow near the orbital plane displays a number of interesting features. Panel (c) which shows the base of the computational plane reveals spiral shocks which occur due to the gravitation effect of the companion. While our simulation can not resolve the Bondi radius of the companion and so can not track wind accretion we note that spiral features such as these were also seen in SPH simulations of disk formation (Mastrodemos & Morris 1998). Note that we see these spiral shocks extend above the equatorial plane in Figure 2 just as did Mastrodemos & Morris (1998). In our case however the spiral shocks above the plane appear closely connected with the wake of the jet. We note that a ring or torus of higher density compressed AGB material appears near the equator. This material is formed via the action of the rotating jet (apparent in Figures 1 and 2 and was predicted by Soker & Rappaport (2000)).

In Fig 3 we show 1-D cuts of density and velocity through the computational space in the xz plane at $x = 80$ AU, which corresponds to the center of the AGB star, and $x = 90$ AU, which corresponds to the initial symmetry axis of the jet. The $x = 80$ AU cut shows a steep rise in velocity which begins at $z = 20$ AU and terminates at $z = 80$ AU. This feature reflects the acceleration of the AGB material as it interacts with the jet. For $z > 80$ AU the line cuts though jet material traveling at close to its injection velocity. The $x = 90$ cut shows a velocity which is approximately constant reflecting the fact that the jet is strong enough that its core remains undisturbed by the AGB material. Note the oscillations in density and velocity which reflect the apparent KH modes along the jet/AGB interface.

To summarize, the interaction of the jet with the slow wind produces a complex morphology composed of multiple shock waves driven into both the AGB wind and jet. In spite of its complexity a quasi-steady state patten does emerge in which the entire flow is embedded in a **V**-shaped shock propagating outward through the AGB wind. The shock produces a dense shell of compressed AGB

material. Within this shell is a cavity produced by the propagating jet which does not assume a strong corkscrew flow pattern because the jet transit time is shorter than the orbital period, *i.e.* jet material moves fast enough that it leaves the grid in a time less than an orbital period $t < T_{\rm o}$. Significant entrainment of AGB and jet material occurs due to shocks at the jet/AGB interface. At the equator spiral shocks are driven into the AGB wind due to the orbital motion of the companion and the effect of the jet.

3.2. Weak jet

We now consider the simulation results for the two cases in which in the momentum in the jet is weaker than that in the AGB wind. As the AGB wind momentum flux becomes successively larger than that in the jet we expect strong shocks to form in the jet beam as well as jet deflections caused the ram pressure of the AGB material . The first weak jet simulation we present has $\chi = 1.25$ and density maps in different orthogonal planes are shown in the Figure 4. The second case has $\chi = 5$ and is shown in Figure 6. Once again, both simulations corresponds to age of 224 years, or 10 orbital periods.

When the flux of momentum of the AGB wind is slightly higher than that in the jet, $\chi = 1.25$, the **V**-shaped shocks in the AGB wind marking the boundary of the interaction region still appear. But, as shown in Fig 4, the effects of the stronger AGB wind are apparent. First it is possible to see a shallow inclination of the jet in panel a) (see left panel detail). For this value of χ the deflection of the entire jet does not occur. Instead, we see a narrowing of the jet on the side facing the AGB in the region at low z, close to the jet source. In the language of Soker & Rappaport (2000) the deflection angle of the jet is still smaller than the collimation angle for these parameters. Thus only the collimation on one side of the jet is affected by the AGB ram pressure.

What is more apparent in this case, as compared to the Strong Jet simulation, is the strong shock in the jet beam. We see a shock and dense shell in panel a) at $z = 100$ AU. Note that the apparent termination of the jet at $z = 100$ AU in panel a), and $z = 280$ AU in panel b) are evidence of its 3-D structure. In panel a) for example, jet material which has been ejected earlier (and is now higher at $z = 100$ AU) will be further up the corkscrew and deeper into the 3-D volume then the position of this xy cut. The dynamically important connection is that the shock decreases velocities in the material surrounding the jet. $T_{\rm cross}/T_{\rm o}$ becomes larger and the orbital motion begins to exert a greater influence on the jet morphology in terms of creating a global "corkscrew" pattern.

Near the equatorial plane and close to AGB star, the flow structure is very similar to the strong jet case. Above the AGB star there is a shock wave and a thin shell of compressed material. This shock can be better appreciated in the 1-D plots in the Figure 5. Here the shock is clearly seen at $z \approx 20$ AU at the z-axis ($x = 80$ AU) and in yz- plane (left panels in the Figure 5). After this shell, the AGB material is gradually accelerated via entrainment reaching a velocity of ≈ 180 km s^{-1}. Using this value in the expression for the crossing time we find $T_{\rm cross}/T_{\rm o} \approx 0.4$.

When χ increases the deflection angle should increase (see Soker & Rappaport (2000), though their expression for the jet bending only applies when the bend occurs on scales smaller than a). Thus for the $\chi = 5$ simulation we expect greater influence of the AGB ram pressure on the jet beam. This expectation is borne out in the xz and yz maps in Figure 6 which clearly show that entire beam has bent away from the AGB star. Globally the cross-sections show a succession of staggered "donkey ear" shaped shocks and dense shells propagating through the AGB wind. Such a pattern was predicted by Soker & Rappaport (2000) and occurs due to the deflection (and disruption) of the jet by the slow wind over an entire orbital cycle.

Consideration of the post-shock velocities in the jet and surrounding material (Figure 7) shows that $T_{\rm cross}/T_{\rm o} \approx 0.86$. With this in mind the enlargement of the xy-plane map in Fig 6 allows us to see the origins of the large scale flow pattern. The jet can be seen emanating from the companion on the right side of the AGB star in panel a). Unlike the Strong Jet case however the jet only propagates to $z \approx 30$ AU before it is shocked via its interaction with the AGB wind. The jet is bounded above by a dense shell comprised of both shocked jet and shocked AGB material. The continuation of this structure can be seen in the yz cross section on the left side of the AGB star.

On the xz and yz planes is possible see, three "ear shaped" lobes, two on panel a) and one on panel b). Each of these features are part of a continuous 3-D structure. What we see in the cuts are cross-sections of shocks formed from the interaction of the jet and AGB wind, each initiated at successive 1/4 $T_{\rm o}$ time delays . Note only three lobes are apparent in the figure implying that jet material ejected in the first 1/4 of the current orbital period has already left the grid. Unlike the Strong Jet case, some of the jet material exits from the side of the grid due to the deflection.

The three dimensional structure of the flow is shown in the Figure 8 for the $\chi = 5$ case. The iso-surfaces in density show have values: 6.168×10^{-18}g cm^{-3}, 5.607×10^{-19}g cm^{-3}, and 1.78×10^{-19}g cm^{-3}, respectively. Lower density iso-surfaces are located at higher z. This figure demonstrates the formation of global corkscrew flow pattern produced due to the orbital motion of the source. Note that we see less than a single turn of the corkscrew as would be expected for the value of $T_{\rm cross}/T_{\rm o}$. The complexity of the flow is also apparent in this figure. The action of multiple shocks passing through the AGB wind and jet creates and a mix of structured and disordered iso-density surfaces. A "donkey-ear" shock is apparent in the middle and lower regions of the computational space. Note also that the spiral shocks in the AGB wind and the global **V**-shaped (in cross-section) shock which bounds the jet/AGB wind interaction is also apparent in this figure. We note that explorations of figures such as these show that the exact choice of iso-density surfaces does not change the qualitative conclusions that can drawn from this figure.

4. Discussion & Conclusions

We have presented new simulations of the interaction of a slow AGB wind with a collimated fast wind (CFW) driven by binary companion. Our binary parameters were selected such that an

accretion disk would form even though we are unable to resolve such a flow pattern. We report three simulations segregated by the ratio of the AGB wind momentum flux to the CFW momentum flux (denoted χ). We simulated a Strong Jet case $\chi = 0.625$ and two Weak Jet cases, $\chi = 1.25$ and $\chi = 5.0$. The binary period was $T_o = 22.4$ years and we carried all simulations out for at least $10T_{\rm o}$.

We find χ to be an effective predictor for differentiating the behavior of the simulations. Strong jets are able to propagate off grid ($Z_{\rm max}$ = 320 AU) without severe deflections or disruptions. When $T_{\rm cross}/T_{\rm o} << 1$, as it was in the Strong Jet case, the orbital motion does not effect the global morphology of the jet. When the jet becomes progressively weaker, and χ becomes larger, we see a trend towards both stronger deflections, (the jet is bent away from the binary), and stronger disruption, (strong shocks bounding the jet beam). The location, in height, of the first shock moves closer to the jet source as χ increases. Weaker jets also lead to more complicated global flow patterns with features such as multiple "donkey ear" shaped lobes appearing at well characterized intervals in height.

Our simulations support the idea that collimated jets, formed close to the central source, are the agents shaping some PN. This paradigm has steadily been gaining favor. Morris (1987) and Soker & Livio (1994) both proposed that jets could be formed via accretion disks in PNe. Sahai & Trauger (1998) proposed that jets formed very early in the PNe or pPNe phase were responsible for the bulk of the nebular shaping with the fast wind from the central star of a PN merely burnishing the details of the nebular shapes. More recently Soker (2002) and Lee & Sahai (2003) have both explored hydrodynamic models of jets driving through circumstellar environments. Our work is complementary to the Lee & Sahai (2003) study in that we examine the flow pattern on smaller scales. Soker & Rappaport (2000) investigated both the hydrodynamics and population statistics of the CFWs and the outflows they would drive in binary systems. They concluded that narrow waisted PNe are likely the result of CFW/AGB wind interactions. Livio & Soker (2001) applied such a model to M2-9 concluding that a weak jet with a severely deflected wind was responsible for both the outflow shape and the shadowing of ionizing radiation from the hot companion.

Our results are most directly relevant to the work of Soker & Rappaport (2000) and can be seen as a test of the ideas put forth there. We find that much of the flow pattern predicted in that work is obtained in our simulations. We do see some evidence for the creation of a region of enhanced density along the equator due to the action of the CFW as predicted Soker & Rappaport (2000). The successive donkey ear lobes seen in the simulations were anticipated by Soker & Rappaport (2000) as well. It is not yet clear if their strong deflection flow pattern will be obtained in real systems however since we are currently not able to resolve details of the jet flow when shocks form very close to the inflow source. We will take up this issue, along with the effects of wind acceleration, in a future study.

Our most important conclusion however is that CFWs do appear as good candidates for creating narrow waisted nebula. The Strong Jet case, in particular, shows that the effect of a

CFW is primarily confined within a **V** or **U** shaped shock in the expanding AGB wind. Such a jet will drive a very narrow waisted flow as there is no expansion along the equator. Thus on large scales the lobes driven by the jet will appear to pinch severely at the outflow source. We note that recent HST observations of the near nuclear regions of M2-9 appear to confirm the flow patterns we see in the Strong Jet case (Balick, private communication 2003) with oppositely oriented **V**-shaped features extending from the unresolved central source out to scales of 10^{15} cm.

This work constitutes a first attempt at mapping out the flow dynamics of outflows driven via binary interactions. Here we have attempted to examine the global properties of the outflows on scales ranging from ≈ 5 to 300 AU. While the use of an AMR code allowed us to capture details such as shocks in the AGB wind and jet beam, the resolution used and limited physics included still leave many open questions. These include the nature of the flow when χ is very large, the role of radiation driving of the AGB wind, the effect of ionizating radiation and the effect of magnetic fields (which should be present if the jets are magneto-centrifugally launched). Inspite of these limitations our simulations provide further support for the argument that jets driven by accretion disks can explain many features observed in bipolar PNe.

We thank Noam Soker for his helpful comments on a draft of this work. B. Balick, P. Varniere, E. Blackman, H. van Horn and J. Thomas for related discussions. Support from the Space Telescope Science Institute, NSF grants AST-9702484, AST-0098442, NASA grant NAG5-8428, DOE grant DE-FG02-00ER54600 and the Laboratory for Laser Energetics. F.G.A. is grateful to CONACYT, México for a posdoctoral scholarship.

REFERENCES

Balick, B. 1987, AJ, 94, 671

Balick, B., & Frank, A. 2002, Annu. Rev. Astron. Astrophys., 40, 439

Blackman, E. G., Frank, A., & Welch, C. 2001, ApJ, 546, 288

Bond, H. E. 2000, in ASP Conf. Ser. 199, Asymmetrical Planetary Nebulae II: From Origins to Microstructures, ed. J. H. Kastner, N. Soker, & S. Rappaport(San Francisco: ASP), 115

Bujarrabal, V., García-Segura, G., Morris, M., Soker, N., & Terzian, Y. 2000, in ASP Conf. Ser. 199, Asymmetrical Planetary Nebulae II: From Origins to Microstructures, ed. J. H. Kastner, N. Soker, & S. Rappaport(San Francisco: ASP), 201

Bujarrabal, V., Castro-Carrizo, A., Alcolea, J., & Sánchez-Contreras, C. 2001, A&A, 377, 868

Cliffe, J. A., Frank, A., & Jones, T. W. 1996, MNRAS, 282, 1114

Corradi, R. L. M., Goncalves, D. R., Villaver, E., Mampaso, A., Perinotto, M., Schwarz, H. E., & Zanin, C. 2000, ApJ, 535, 823

Doyle, S., Balick, B., Corradi, R. L. M., & Schwarz, H. E. 2000, AJ, 119, 1339

Dwarkadas, V., Chevalier, R. A., & Blondin, J. M. 1996, ApJ, 457, 773

Frank, A. & Blackman, E., 2003, ApJ, submitted

García-Segura, G., Langer, N., Różyczka, M., & Franco, J. 1999, ApJ, 517, 767

Icke, V., Balick, B., & Frank, A. 1992, A&A, 253, 224

Icke, V., Preston, H. L., & Balick, B. 1989, AJ, 97, 462

Konigl, A., & Pudritz, R. E. 2000, in Protostars and Planets IV, ed. V. Manning, A. P. Boss, & S. S. Russell, (Tucson: Univ. Ariz. Press), 759

Lee, C., & Sahai, R. 2003, ApJ, 586, 319

Livio M. 1993, in Planetary Nebulae, IAU Symp. 155, Planetary Nebulae, ed. R. Weinberger, & A. Acker, (Dordrecht: Kluwer), 279

Livio, M., & Soker, N. 2001, ApJ, 552, 685

Livio M., Soker, N., de Kool M., & Savonije, G. J. 1986, MNRAS, 222, 253

Mastrodemos, N., & Morris, M. 1998, ApJ, 497, 303

Mastrodemos, N., & Morris, M. 1999, ApJ, 523, 357

Mellema, G. 1995, MNRAS, 277, 173

Mellema, G. 1997, A&A, 321, 29

Morris, M. 1987, PASP, 99, 1115

Raga, A. C., Cantó, J., & Biro, S. 1993, MNRAS, 160, 263

Raga, A. C., Navarro-González, R. & Villagrán-Muñiz, M. 2000, RMxAA, 36, 67

Raichoudhuri, A. 1998, The Physics of Fluids and Plasmas (Cambridge:University of Cambridge)

Sahai, R.,& Trauger, J. T. 1998, AJ, 116, 1357

Schwarz, H. E., Corradi, R. L. M., & Melnick, J. 1992, A&A, 96,23

Soker, N. 2002, ApJ, 568, 726

Soker, N., & Rappaport, S. 2000, ApJ, 538, 241

Soker, N., & Livio, M. 1994, ApJ, 421, 219

Van Leer, B. 1982, ICASE Report No. 82-30

Fig. 1.— Strong Jet greyscale density maps of cross sections in the a) xz plane, b) yz plane, and c) xy plane (*i.e.* the equatorial plane). Panels on both sides of plot c) are enlargements of the plots a) and b). The white dots are the position of the center of the stars. The units in the axises are given in AU. The grayscale is the logarithm of the density.

Fig. 2.— Three-dimensional volume rendering of velocity along with density iso-surface (wire-mesh). The axises are given in pixels. The velocity scale is 1 to 100 km s^{-1} with dark scales representing high velocity. The wire mesh shows an iso-surface at $\rho = 3.4 \times 10^{-18}$ g cm^{-3}.

Fig. 3.— Cuts in velocity and density. The left top panel is the velocity along a vertical line at $x = 80$ AU (the center of the AGB star). The bottom left panel is the density along the same line. The right panels are taken at $x = 90$ AU (approximately the position of the jet).

Fig. 4.— Weak Jet greyscale density maps of cross sections in the a) xz plane, b) yz plane, and c) xy plane (*i.e.* the equatorial plane) with $\chi = 1.25$. Panels on both sides of plot c) are enlargements of the plots a) and b). The gray scale is the logarithm of the density.

Fig. 5.— Cuts in velocity and density for a $\chi = 1.25$ simulation. The left top panel is the velocity along a vertical line at $x = 80$ AU (z-axis). The bottom left panel is the density along the same line . The right panels are similar, but they taken are at $x = 90$ AU (approximately the position of the jet)

.

Fig. 6.— Greyscale density maps like in the Figure 1, but for $\chi = 5$.

Fig. 7.— Cuts in velocity and density as in the Figure 5 but for $\chi = 5.0$

Fig. 8.— Isosurfaces of the density with values of 6.168×10^{-18}g cm^{-3}, 5.607×10^{-19}g cm^{-3}, and 1.78×10^{-19}g cm^{-3}. The units in the axises are given in pixels like in the Figure 2.

This figure "f4.jpg" is available in "jpg" format from:

http://arXiv.org/ps/astro-ph/0307454v1

This figure "f5.jpg" is available in "jpg" format from:

http://arXiv.org/ps/astro-ph/0307454v1

This figure "f6.jpg" is available in "jpg" format from:

http://arXiv.org/ps/astro-ph/0307454v1